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San Francisco | Bulletin 170 | September 1954

GEOLOGY OF SOUTHERN CALIFORNIA

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CHAPTER X
ENGINEERING ASPECTS OF GEOLOGY

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Editorial Note:

CHAPTER TEN deals with several of the more serious geologic problems that confront the resident of southern California. The highly varied topography and climate of the region, together with the complexity of its rocks and their structure, form a background of physical factors that cannot be ignored in the development of this region by man. Some of these factors are related directly to floods, earthquakes, mass movement of ground, and other recurring events over which man has little fundamental control, and others are developed by some of man's own activities. Failure to anticipate or properly to evaluate these factors during past development of the region has led to unfortunate, and at times disastrous, consequences.

Only during recent years has there been widespread recognition of the need for careful geologic appraisal of engineering problems in southern California. Normal study of the positive factors in location and design of buildings, dams, aqueducts, and other structures, for example, is now being supplemented by consideration of the nature and movement of solid and liquid materials in the subsurface, the position and behavior of active faults in the area, the movement of surface water in the area during previous centuries, and other features that are likely to have significant long-term effects. Typical avenues of geologic approach to several major engineering problems are discussed in the three papers that make up this chapter.

CONTENTS OF CHAPTER X

1. EARTHQUAKES AND EARTHQUAKE DAMAGE IN SOUTHERN CALIFORNIA*

By Charles F. Richter †

Intensity Scales

Although problems of the seismic activity of any region or of the world are best handled in terms of the earthquake magnitude scale, this scale will not serve the needs of the engineer and field geologist who wish either to relate effects on structures, ground, and ground water to the intensity of local shaking, or to interpret intensity in terms of surface and subsurface structure and the generating mechanism of earthquakes. The magnitude scale attaches a single number to the earthquake as a whole (see Richter and Gutenberg, Contribution 3, Chapter IV); for detailed statement of the variation of effects from point to point an intensity scale is needed.

Ideally, intensity should be determined from complete instrumental recording of motion at the point in question. Seismographs commonly in use have high magnifications, run off the recording sheet if the motion is strong enough to be felt, and are put out of action by high intensities. Strong-motion seismographs have been constructed with low magnification, usually triggered to begin recording during a locally strong earthquake, but even these instruments are expensive to construct and maintain. In the last 20 years many records have been obtained from such instruments, chiefly in California, by the U. S. Coast and Geodetic Survey. They represent the motion at only a few localities for each earthquake.

Mr. Frank Neumann, at the Coast and Geodetic Survey office in Washington, is now engaged in a synthetic study of these records—a study aimed at placing the intensity scale on a sound physical basis. It is not yet possible to anticipate final results in this direction. The many thousands of seismograms of earthquake motion too small to be felt show a complexity and a difference between individual shocks which indicate that generalizations should be undertaken only with great caution; further, there is good reason for believing that the vibrations are still more complex in large earthquakes.

Under these circumstances, intensity still must be rated in the established fashion, i.e., from field observations of the effects on structures, loose objects, and the ground itself. Long experience shows that certain earthquake effects tend to appear together as the intensity increases, and the published scales consist of a grouping of such effects under a series of arbitrary grades, which are usually designated by Roman numerals to emphasize that the intensity number does not stand for a physically measured quantity. Many efforts have been made to correlate these intensity numbers with some physical element of the earthquake motion, usually acceleration. Such a relation is that published by Gutenberg and Richter (1942):

$$\log a = I/3 - 1/2$$

Here I is the intensity number on the modified Mercalli scale of 1931, and a is acceleration in cm sec^2. It must be emphasized that this relation is extremely rough and empirical, and by no means should be used for any precise work.

The Rossi-Forel scale, commonly used and best known for many years, is as follows:

1. *Microseismic shock.*—Recorded by a single seismograph or by seismographs of the same model, but not by several seismographs of different kinds; the shock felt by an experienced observer.
2. *Extremely feeble shock.*—Recorded by several seismographs of different kinds; felt by a small number of persons at rest.
3. *Very feeble shock.*—Felt by several persons at rest; strong enough for the direction or duration to be appreciable.
4. *Feeble shock.*—Felt by persons in motion; disturbance of movable objects, doors, windows; cracking of ceilings.
5. *Shock of moderate intensity.*—Felt generally by everyone; disturbance of furniture, beds, etc.; ringing of some bells.
6. *Fairly strong shock.*—General awakening of those asleep; general ringing of bells; oscillation of chandeliers; stopping of clocks; visible agitation of trees and shrubs; some startled persons leaving their dwellings.
7. *Strong shock.*—Overthrow of movable objects; fall of plaster; ringing of church bells; general panic; without damage to buildings.
8. *Very strong shock.*—Fall of chimneys; cracks in the walls of buildings.
9. *Extremely strong shock.*—Partial or total destruction of some buildings.
10. *Shock of extreme intensity.*—Great disaster; ruins; disturbance of the strata, fissures in the ground, rock falls from mountains.

When the imperfections in this scale became increasingly evident, an improved scale was constructed by Mercalli. This still retained too close reference to conditions that were specifically European, so that the modified Mercalli scale of 1931 was constructed for application in the United States, especially in California, with the intention of retaining general applicability as far as possible. Its summarized form is as follows:

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FIGURE 1. Relief map of southern California showing areas where significant structural damage has been caused by earthquakes during the period 1812-1952.

I. Not felt except by a very few persons under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all; many persons frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.

VIII. Damage slight in specially designed structures; considerable and with partial collapse in ordinary substantial buildings; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well waters. Disturbs persons driving in motor cars.

IX. Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great damage in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

XI. Few, if any, masonry structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

Anyone working with actual data should use the complete form of this scale. The Rossi-Forel scale, which included reference to different types of instruments that were not specified, rapidly became obsolete. Similarly, the 1931 scale refers to different types of construction that are not specified closely. Its authors had in mind the construction conditions that were prevailing in 1931, especially in California, as revealed by damage in a large number of earthquakes. Since that time there has been much construction under better conditions of design and inspection; thus, too literal application of the 1931 scale to new structures may lead to an underestimating of intensity. Unfortunately for the community, but fortunately for the intensity scale, many of the older, weaker structures still remain, and by their bad performance provide a check against the response of better designed construction to a shock of given intensity.

The following points are particularly to be noted in applying any intensity scale:

1. Intensity assignments should be based on the entire complex of effects in a given locality; no one criterion should be singled out for use, especially if the evidence is conflicting.

2. Intensity should be that which best represents effects in the locality, aside from individual departures due to peculiarities of structure, ground, or to propagation of elastic waves. It should not

FIGURE 2. Damage to weak masonry, El Centro, 1915. Seis. Soc. Amer., Bull., vol. 5, plate 14.

FIGURE 3. Damage to weak masonry, Inglewood, 1920. Separation of bricks was due to weak mortar. Seis. Soc. Amer., Bull., vol. 10, plate 8. *Photo by Los Angeles Times.*

FIGURE 4. Damage to weak masonry, frame structure with brick veneer, Santa Barbara, 1925. Seis. Soc. Amer., Bull., vol. 15, plate 30.

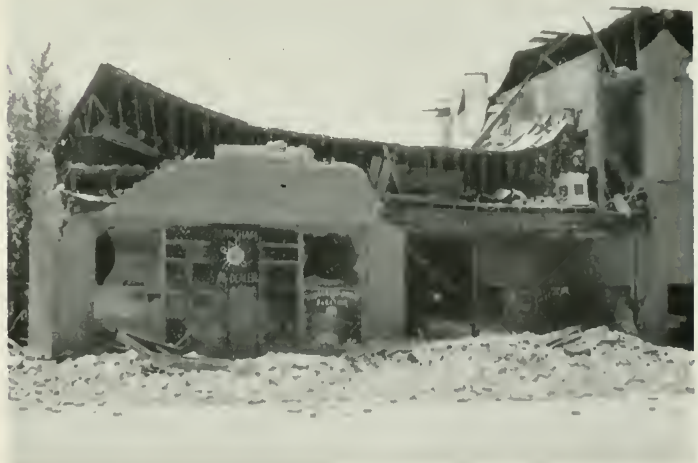

FIGURE 5. Severely damaged building housing Masonic Lodge, Tehachapi, 1952. *Photo by F. E. Lehner.*

be the highest suggested intensity number, nor the lowest; in statistical terms, it should be the mode.

3. How minutely local effects can be considered depends on available information. In the absence of very full data, as in thinly settled areas, care must be taken to consider the effect of ground at the point of observation. Other circumstances being equal, apparent seismic intensity is higher on unconsolidated ground (alluvium, especially where water-soaked; beach sands; artificial fill) than on consolidated ground or on firm rock. This is in part due to slumping, settling, and disturbance of ground water, induced by earthquake vibration. It has also been attributed directly to decrease in velocity of seismic waves entering the less consolidated material. Whatever the cause, this effect normally masks the more naturally expected "cushioning," or absorption of elastic waves passing through soft material. Such cushioning probably occurs to some extent, but in estimating any risk at a given locality, or in drawing any inference from local intensity as to the source of an earthquake, it first should be assumed that intensity is increased in soft ground.

In assigning intensity to an extended area, as in point 2 above, allowance should be made for this effect of ground. Thus small local areas of high intensity that obviously are due to bad ground normally do not appear in isoseismal maps. This may not be best for the structural engineer, but it is convenient for the geologist who is trying to investigate the nature and degree of disturbance in the underlying "basement" rock.

4. Intensity scales combine three principal groups of effects which do not always show close correlation: those due to short-period and to long-period elastic waves, and those due to fault displacement.

Most ordinary effects on structures are due to waves with short periods (0.1 second to 1 second) but relatively high accelerations (100 cm/sec^2 or over). Many effects on large structures, and many of those involving large-scale slumping, sliding, and disturbance of ground water, are connected with waves of period as much as ten seconds, having low accelerations but amplitudes measured in inches or even feet. Such waves are particularly prominent in large earthquakes, especially where there is evidence for considerable linear extent of faulting.

Intensity may not be exceptionally high as measured by elastic-wave vibration in the vicinity, especially when a fault break reaches the surface through unconsolidated material. This was the case in the Imperial Valley earthquake of 1940. At Cocopah (Mexico) an adobe structure straddling the fault trace, where there was a strike-slip displacement of nearly 10 feet, was torn apart and wrecked; in contrast, adjacent structures of the same type, though damaged, were in not much worse condition than others several miles from the fault.

FIGURE 6. Cummings Valley School, west of Tehachapi, 1952. Constructed prior to 1933 of concrete that was nominally but not effectively reinforced. *Photo by State Division of Architecture.*

In applying the intensity scale, it is difficult to eliminate inconsistencies that arise from these causes; they show that the idea of intensity is complex and includes distinct physical quantities that ultimately must be separated.

Damage to Structures

The following notes refer chiefly to damage by elastic waves, usually involving accelerations exceeding one-tenth that of gravity. Very serious damage often is occasioned by slumping or settling, as well. In many instances such mass movements take place in an unstable area that obviously is unsuitable for habitation, and in which the slumping and settling are constantly going on and are merely triggered or accelerated by earthquakes.

Most ordinary structures will not withstand distortion of their foundations. Special construction, however, can be made surprisingly resistant, as shown for example, by the city hall at Lynwood. In anticipation of possible settling in soft ground, this brick building was reinforced at each floor level by diagonal bracing, and a course of cement was laid after every few courses of brick. This structure withstood the Long Beach earthquake of 1933 with almost no damage, whereas most brick structures in the immediate vicinity were seriously damaged and some were almost completely wrecked.

This bears on the vexing question of safe brick construction in an earthquake region. The comments that follow are strictly the writer's own, and he assumes full personal responsibility for them.

As a matter of history, brick construction has had a poor record in connection with California earthquakes. This is due in large measure to fundamentally unsound building practices that obtained during the "boom" period of the 1880's, and which continued in lesser degree down to 1925 and 1933. For many years there was no effective building inspection, especially in smaller communities; such regulations as were enforced were directed against fire and other more frequent risks, and did not consider earthquake risk at all. Some structures were so jerry-built that they developed cracks and failed partially under normal use and loading. Some were repeatedly condemned, nominally repaired in slapdash fashion, and returned to use. Few structures of any type were designed to withstand lateral forces. Extensive falling out of walls at Santa Barbara in the 1925 earthquake drew attention to failure to tie in at the corners, a precaution that has been incorporated in later building codes.

Mortar often has been of poor quality or poorly applied. When a California brick structure is cracked by earthquake motion or by other causes, the cracks almost invariably pass around the bricks, not through them. The Long Beach earthquake of 1933 developed a vast supply of good second-hand bricks; jobbers found that bricks from damaged structures could be cleaned perfectly by hosing off the remains of the mortar, leaving them as good as new.

These evils are not necessary, as the above example of the Lynwood city hall shows. However, in commercial masonry work it is very difficult for the contractors to maintain high standards and still make a profit. Best results, for example, are believed to be obtained by laying up the bricks wet and allowing each course to dry before adding the next. This is a slow and expensive process.

Safer structures have been obtained by making a frame of steel or reinforced concrete, and by using brick principally for filling and facing. Such buildings have behaved comparatively well during recent earthquakes, and actually have been responsible for underestimation of earthquake intensity in their vicinity.

For public buildings, and especially schools, much was accomplished by passage of the Field Act shortly after the Long Beach earthquake. This sets improved standards, including earthquake resistance, for new public construction, and places the responsibility for the safety of old structures on the individual communities, with the State Department of Public Works as inspecting agency. Attempts to weaken the provisions of this legislation have been made almost continuously—so far, fortunately, with no great success.

Ordinarily well-built frame structures are not particularly susceptible to damage, especially in moderate earthquakes. If not well braced diagonally, the frame may be badly wrenched. If the structure is not properly bolted to its foundation, it may slide off and

FIGURE 7. Collapse of weak frame structure. Hotel in San Jose, 1906. California Earthquake Commission Report.

FIGURE 8. Barn not seriously damaged, although fault trace passed under one corner, 1906. Near Olema. California Earthquake Commission Report

hence be seriously damaged. In the 1933 earthquake there was damage to many frame structures supported on vertical posts termed "cripples." As already suggested, steel-frame and reinforced concrete structures, up to moderate size, have performed well except where there were obvious deficiencies in design or workmanship.

The safe design of large structures presents serious difficulties, as the complexity of the dynamical properties of such a structure, combined with the extreme complexity of strong earthquake motion, place the general problem almost beyond the reach of exact analysis. Much progress has been made by investigating the behavior of models on shaking tables, but serious differences of interpretation and opinion still remain among competent specialists. The design problem is now being met by the introduction of safety factors well beyond the limits of any anticipated stress, and by rigid county and city regulations.

Earthquake Risk and Geography

The accompanying map (fig. 1) shows communities and areas in southern California where serious earthquake damage (intensity VIII or over, modified Mercalli 1931) has occurred during the relatively brief period of historic record. Naturally these indications are infrequent in the thinly populated desert and mountain regions. The fact that any one community has escaped in the short time of record is no guarantee of future immunity. It will be noted that the distribution of earthquake damage is rather general.

It is commonly assumed that earthquake risk in southern California is concentrated exclusively near the major faults. This is not the case. At a given point the principal long-term risks involve a great earthquake originating on one of the major faults, up to distances of as much as 50 miles, or a comparatively moderate earthquake, like the Santa Barbara and Long Beach shocks, originating nearby. The distribution of seismicity in California (Contribution 3, Chapter IV) is such that this combination of risk can be considered relatively even over the region. Increased risk is much more a matter of ground. The chief danger spots are the alluviated areas of both coast and interior, and the areas of artificial fill in metropolitan zones. To these must be added the major fault zones, where the crushed and unconsolidated material adds to the probability of damage, even from earthquakes originating elsewhere.

In California, and especially in the more arid sections, disturbance of ground water is a potential source of heavy economic loss. Thus in 1952 there was great loss in Kern County due to failure of wells and springs, which was aggravated by damage to pipe lines and tanks. A less direct effect threatened to be extremely serious; many transformers were thrown down from poles, cutting off power supply to well pumps used for irrigating cotton fields. This was greatly mitigated, however, by prompt emergency action of power-company crews. In 1940 there was very great loss in the Imperial Valley by damage to the irrigation system, partly by disturbance and ejection of ground water (an effect that was still more serious in the Yuma Valley), and partly by fracture and offset of the major canals where they crossed the fault along which movement took place.

The risk of fire after a damaging earthquake is well known, especially since the San Francisco disaster of 1906, when the fire spread unchecked because of water-supply failure. This lack of water was due to destruction of pipe lines near the San Andreas fault. In 1933 the fire-alarm system at Long Beach was put out of action, but the fire companies patrolled their several districts and extinguished many small fires.

Thus, although most direct earthquake damage is due to shaking, the immediate effects of faulting are confined to a narrow zone. There is serious risk of heavy loss by interruption of long-distance utility supplies of all kinds wherever they cross the fault. Effects of interruption of railroad and highway communication also should be considered.

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